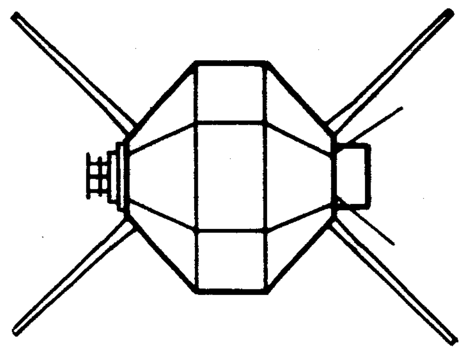
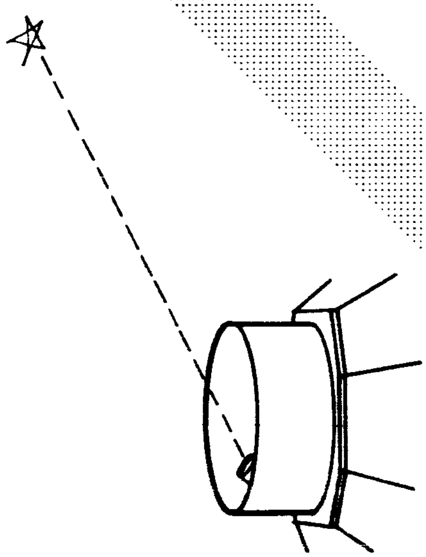
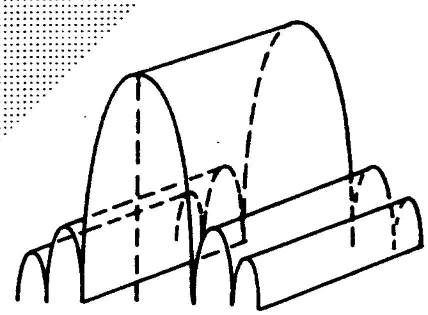
13 JULY 1966

VOLUME I
SUMMARY

FAN BEAM NAVIGATION SATELLITE STUDY







CONTRACT
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Submitted to

HEADQUARTERS NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C.

PHILCO | WDL DIVISION
A SUBSIDIARY OF Ford Motor Company
PALO ALTO · CALIFORNIA
HOUSTON · TEXAS

WDL TECHNICAL REPORT 2962

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VOLUME I

SUMMARY

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Submitted to:

Headquarters
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Prepared by

PHILCO CORPORATION
A Subsidiary of Ford Motor Company
WDL Division
Palo Alto, California

FOREWORD

This is the final report for NASA Contract NASW-1368. The work was performed under the technical direction of NASA Electronic Research Center, Boston, Massachusetts. The results of the study are reported in five volumes as described below.

Volume I	Summary of study results
Volume II	Dynamic simulations of the satellite-navigator system
Volume III	Analytical studies and dynamic simulations of the antenna patterns.
Volume IV	Electrical and power subsystem studies.
Volume V	Definition of a flight test experiment for a small spinning satellite.

ACKNOWLEDGEMENTS

Listed below are the personnel of Philco WDL who made primary contributions to this study program in the technical areas indicated.

S. F. Schmidt	Project Manager
R. C. Jensen	Study Leader
R. S. Davies	Electrical Subsystem Studies
J. G. Gibson	Electrical Subsystem Studies
K. C. Ward	Electrical Subsystem Studies
F. J. Zobel	Antenna Propagation Studies
R. F. Rudolph	Antenna Propagation Studies
W. J. Young	Antenna Structural Analysis
H. B. Lee	Antenna Structural Analysis
J. W. Patmore	Antenna Pattern Simulation
R. H. Tibbitts	System Simulation Studies
W. S. Bjorkman	Specialized Simulation Studies
A. L. Jett	Experiment Design
R. I. Nakanishi	Experiment Satellite Layout
D. S. Ross	Star Detector Preliminary Design
E. W. Onstead	Experiment Mission Analysis
A. E. Aho	Technical Editing

Mr. Richard Trueblood of GM Defense Research Laboratories contributed information to the study on passive nutation dampers.

Mr. Michael Smith of Applied Technology Incorporated contributed information to the study on receiver cost.

Mr. Leo Keane of NASA Electronic Research Center monitored the study and provided technical assistance in all study areas.

Mr. Eugene Ehrlich of NASA Headquarters provided the initial incentive to pursue this navigation concept to its current state of development.

INTRODUCTION

The intent of this work was to conduct a feasibility study of the Fan Beam Navigation Satellite concept proposed in 1964 by Dr. Stanley F. Schmidt of Philco WDL. This study included investigations covering the following items:

- Satellite Antennas, Attitude Control and Attitude Sensing and Dynamic Simulation
- Receiver and Detection Analysis
- System Calibration and Fix Computations
- Definition of an Experiment

Investigations in each of the areas were conducted in sufficient analytical depth to firmly establish the feasibility of the proposed technique. At the completion of the analytical studies an experiment was defined which could provide a flight test verification of the derived results. Parametric results were also obtained relating to the specification of a satellite for a world-wide operational Fan Beam Navigation System.

SUMMARY

The results of this study are summarized using a question-and-answer format for the basic areas of investigation. The following pages present selected questions and corresponding answers. A more detailed description of information and results leading to these answers is presented in Volumes II through V.

Number	Area	Question
1	Concept	What are the principles of operation for this concept?
2	Implementation	What are the basic elements required to implement the fan beam concept?
3	Concept	Is the fan beam navigation concept capable of producing fix accuracies of less than one nautical mile?
4	Operation	May this concept be utilized in either a passive or semi-active mode of operation?
5	Frequency	At what frequency does this concept appear most feasible for implementation?
6	Antennas	Is the length of the antenna necessary to achieve the level of accuracy previously mentioned reasonable for a spinning satellite?
7	Power	Are the satellite powers required for this accuracy level realistic in terms of satellite size and weight?
8	Attitude	Does the satellite attitude control require some type of passive damping?
9	Attitude	Is there a way to determine the satellite spin axis to the required accuracy?
10	Receiver	Is the required user receiver antenna relatively small?
11	Receiver	Does the receiver antenna require pointing?
12	Receiver	Is the receiver within state-of-the-art solid-state electronic capability?
13	Receiver	Does the cost of the receiver equipment appear to be compatible with a wide variety of users?
14	Calibration	Does the system calibration appear to lend itself to long time intervals?
15	Computation	Could the fix computation required by a user be a relatively simple calculation?
16	Reference	Does the reference channel required for this concept appear feasible to implement?
17	General	Should additional studies or tasks be carried out to refine any aspects of the system concept?
18	Experiment	Is there a reasonable experiment which could be used to flight test this navigation concept before implementation of an operational system?
19	Communication	Does this navigation concept allow for any other satellite communication services?
20	General	Would you recommend this navigation concept for use as an operational system?

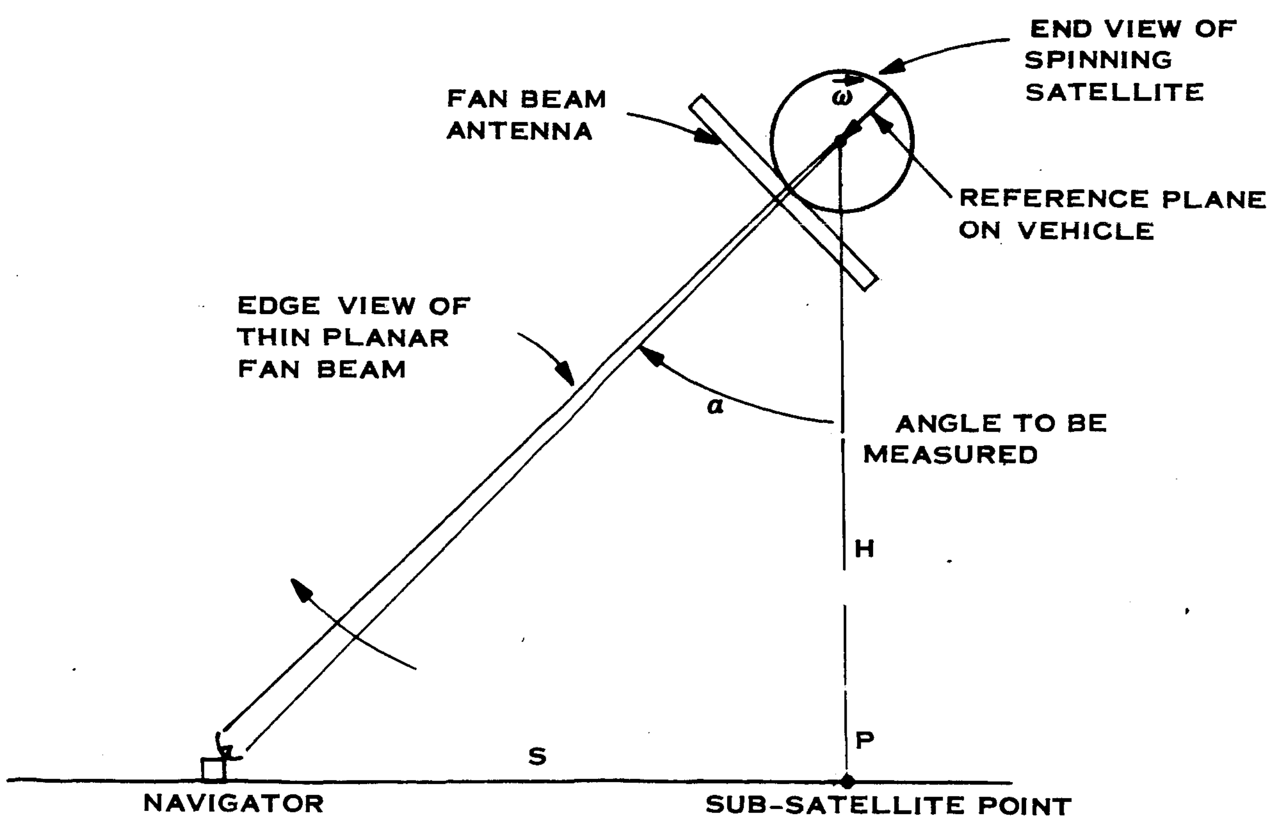
QUESTION 1

Q. What are the principles of operation for this concept?

A. This concept employs basically time measurements by the navigator from which two separate angles are determined.

Explanation

A schematic showing how a single angle measurement can be made using a single fan beam on a spinning satellite is shown below. The sequence of operation is given on the following page.



Sequence of Operation

1. A signal is transmitted from satellite to navigator when the "Reference Plane" contains the sub-satellite point(P). Hence, a reference time (T_R) is established by the navigator.
2. Navigator detects passage of fan beam at time (T_1) as it sweeps by his receiver.
3. Navigator computes angle (α) as shown on schematic from the equation

$$\alpha = \omega \left(T_1 - T_R\right) + \alpha_o$$

   where

   ω = spin rate

   α_o = angle between reference plane and fan beam plane on satellite

4. Knowing the altitude of the satellite (H) and the computed angle (α), the navigator may compute his position (S) relative to the sub-satellite point (P).

$$S = H \tan \alpha$$

Expanding the description to include an additional fan beam merely adds the requirement for the navigator to compute one more angle. It is also obvious that the navigator must have information about his altitude since two angle measurements may only lead to a knowledge of the direction of the user relative to the satellite.

For the case of two orthogonal fan beams bisected by the satellite spin axis, some simple but interesting conclusions may be derived. Figure 1 shows lines of constant time sum (the time average of the two fan beam passages relative to the reference time) and lines of constant time difference (the time difference between the passage of the two fan beams). For a 5000 n. mi. altitude satellite spinning at 3 rps, the circles are lines of constant distance from the sub-satellite point in nautical miles. There is an obvious correlation between the lines of constant time sums and differences and latitude-longitude lines. In the vicinity of the sub-satellite point the time sum-difference grid could be used for a graphical method of determining navigator position.

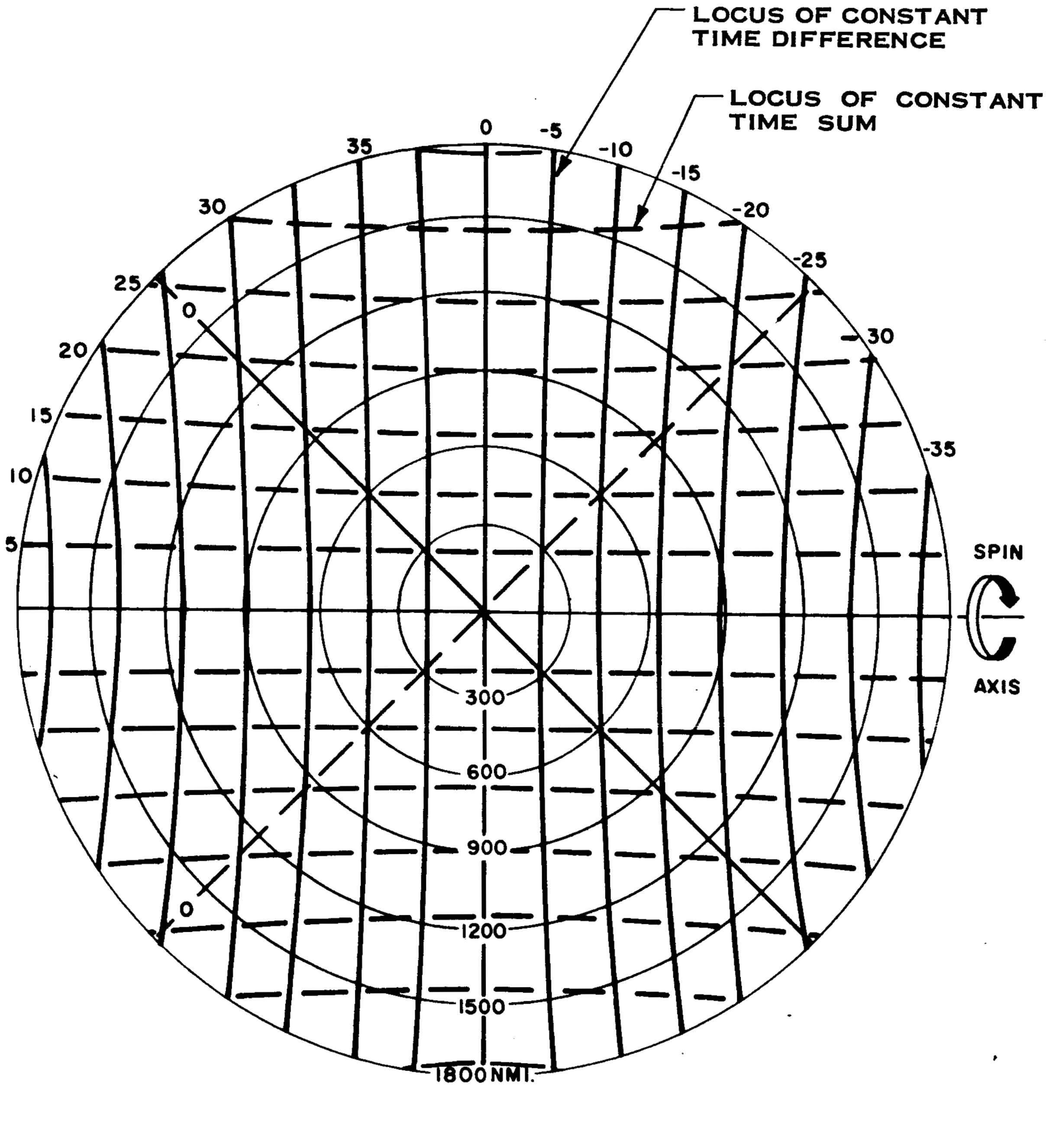


Figure 1 Loci of Constant Sums and Differences of Fan Beam Intercept Times

QUESTION 2

Q. What are the basic elements required to implement the fan beam concept?

A. Explanation.

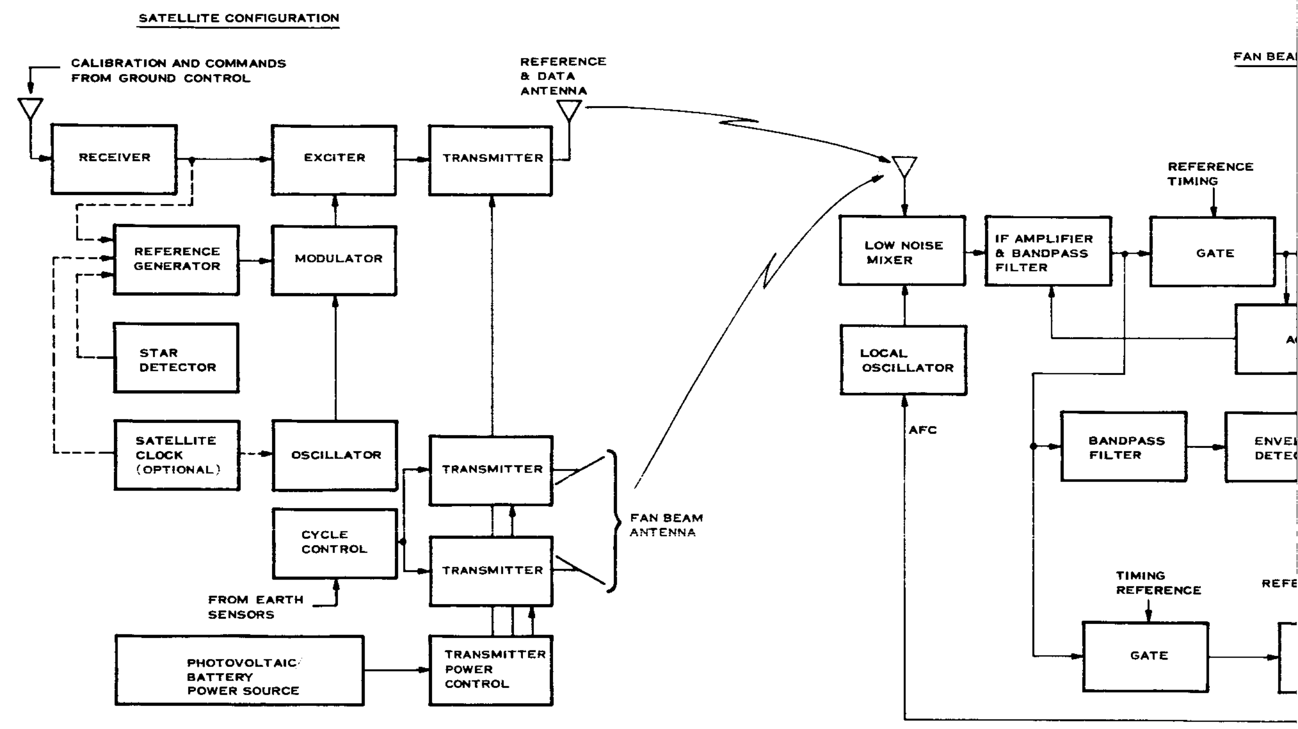
The fan beam navigation concept consist of the basic elements listed below and as shown in the block diagram in Figure 2.

Satellite

- A spin-stabilized satellite with some form of spin-axis damping
- A photovoltaic/battery power supply
- One or more transmitters depending on the proposed configuration
- Two slotted waveguide antennas for operation in the 4 GHz-8 GHz frequency range
- Receiving and transmitting antennas for communication, data link, and reference signals
- A star detector or a satellite clock, combined with a data channel for generating and transmitting reference pulse information.

Navigator

- An antenna to receive fan beam passages, reference signals, and provide a data link with the satellite
- An envelope detector
- A simple threshold detector for determining fan beam passage times
- A simple digital computation device for averaging fan beam passage times and converting time measurements into position coordinates
- A display device which would provide a continuous monitoring of the computed results.


SATELLITE CONFIGURATION
CALIBRATION AND COMMANDS FROM GROUND CONTROL
RECEIVER
EXCITER
TRANSMITTER
REFERENCE & DATA ANTENNA
REFERENCE GENERATOR
MODULATOR
STAR DETECTOR
SATELLITE CLOCK (OPTIONAL)
OSCILLATOR
TRANSMITTER
CYCLE CONTROL
TRANSMITTER
FAN BEAM ANTENNA
FROM EARTH SENSORS
PHOTOVOLTAIC BATTERY POWER SOURCE
TRANSMITTER POWER CONTROL
LOW NOISE MIXER
IF AMPLIFIER & BANDPASS FILTER
REFERENCE TIMING
GATE
LOCAL OSCILLATOR
AFC
BANDPASS FILTER
TIMING REFERENCE
GATE

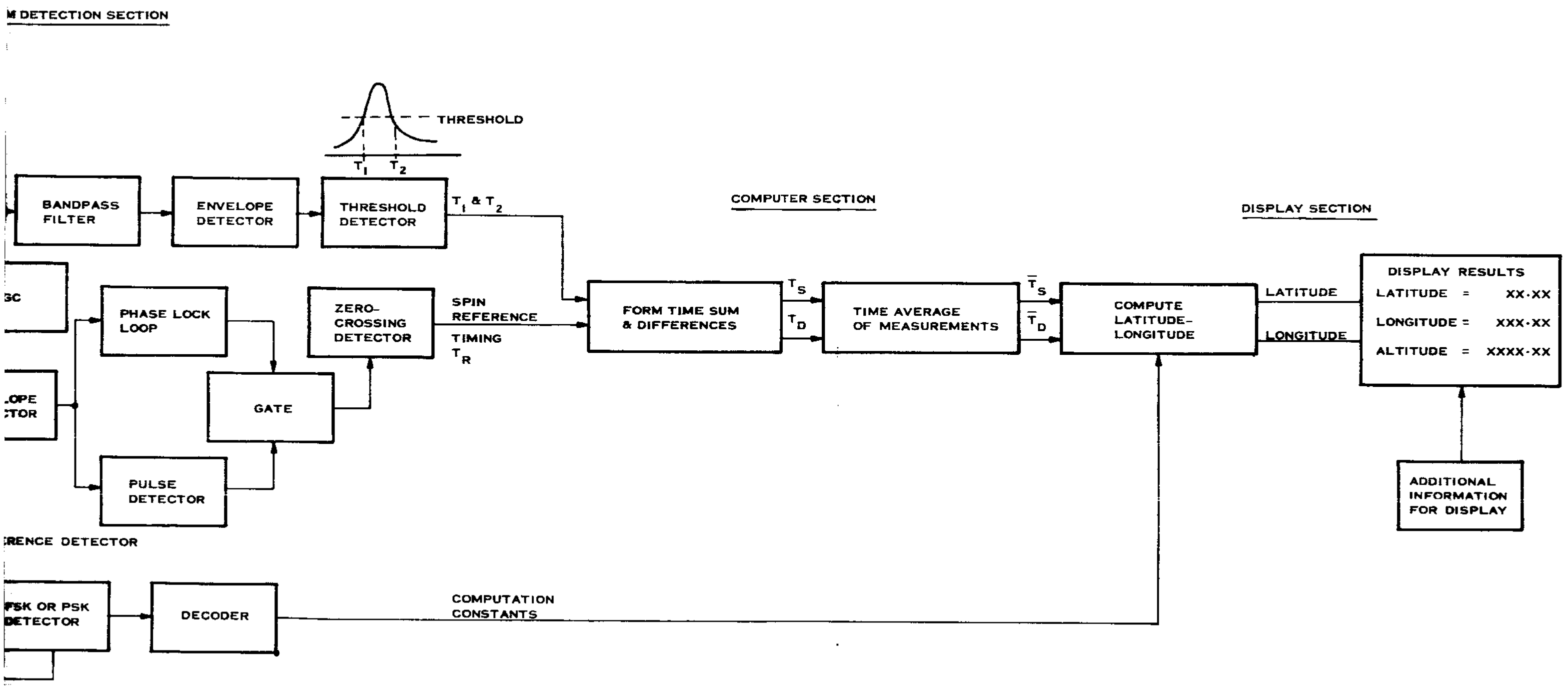


Figure 2 Block Diagram, Navigator Receiver Configuration

QUESTION 3

Q. Is the fan beam navigation concept capable of producing fix accuracies of less than one nautical mile?

A. Yes.

Explanation. (Volume II)

The concept as investigated in this study is easily capable of producing fix accuracies of one nautical mile or less using reasonable satellite powers, and reasonably inexpensive receiver equipment.

Simulations were performed for two satellite altitudes: 5000 and 19311 n. mi. Various navigator locations relative to the satellite were assumed.

It was found that timing errors due to a finite (i.e. non-ideal planar) antenna pattern are correlated closely with the difference of the two fan-beam detection times, and are independent of particular navigator locations. These errors can thus be removed in calibration. Fix errors due to earth and satellite orbital motion and independent navigator motion appear to be insignificant except for the most demanding navigation requirements. For small errors in the navigator's knowledge of the satellite angular velocity vector direction, the consequent fix error varies linearly. A relatively simple type of calibration should make this effect inconsequential. Errors in knowledge of the orientations of the satellite antenna booms at prescribed reference times result in fix error curves somewhat different from those for angular velocity errors, and can cause more severe fix errors. For the same navigator site, the higher altitude satellite yielded smaller fix errors than the lower for these studies in which no noise was assumed to exist.

When N fixes in sequence are examined it is found that typical fix error curves oscillate with a non-trivial amplitude, due to the changing satellite attitude. A single fix can easily "catch" the satellite in an unfavorable attitude. When a set of 11 fixes is averaged, very good results are obtained. When noise is applied to fan timing measurements, longer smoothing times are beneficial. Also, because of lower signal-to-noise ratios the higher satellite fixes are less accurate than the lower, for the same navigator site. It was found that a simple "time smoothing" technique is equivalent to smoothing fully calculated fixes. Finally, simulated "operational" Navigation Satellite cases were run, in which satellite transmitter power, satellite antenna length and receiver antenna diameter were varied parametrically. Results are given in Volume II.

For example, a position accuracy of one nautical mile can be obtained for the following system constants:

Satellite altitude	=	Synchronous
Satellite RF power	=	100 watts
Satellite antenna length	=	8 feet
Receiver dish size	=	5 inches
Receiver noise temperature	=	$1000^{o}K$
Measurement smoothing time	=	30 seconds

QUESTION 4

Q. May this concept be utilized in either a passive or semi-active mode of operation?

A. Yes.

Explanation. (Volume II and Volume IV)

The fan beam concept particularly lends itself to a passive mode of operation. For the idealized passive mode of operation, only the two fan beams and the time reference signal would be continuously transmitted to the user. Information relating to satellite position and spin-axis orientation would be either stored on board the user vehicle or periodically communicated via the navigation satellite. The frequency of this information transfer would be quite low if a synchronous station-kept navigation satellite were employed.

Another interesting feature of this mode of operation is that the passive and semi-active modes could be combined. For example, fishing vessels could be entirely passive and act in a listening capacity only, whereas commercial aircraft could be semi-active and hence re-transmit time measurements through the satellite to an air traffic control center. This mode of operation would allow the aircraft to have its own self-contained position determination capability as well as providing information for the air traffic control center.

It is concluded that the Fan Beam Navigation Satellite concept could be implemented in either one or both of these modes of operation, passive and semi-active, depending on user requirements. The fully active mode of operation was not investigated in this study primarily due to time limitations.

QUESTION 5

Q. At what frequency does this concept appear most feasible for implementation?

A. Explanation. (Volume IV)

The best frequency range for implementation of this concept appears to be between 4 and 8 GHz. At frequencies lower than 4 GHz the size of the linear array on the spinning satellite introduces severe structural problems leading to large support members and poor accuracies. Power tubes are being developed at or near the frequency of 4 GHz which could be used to provide CW transmitter output powers of 75 to 100 watts. At frequencies above 8 GHz the satellite antenna problem is diminished but the availability and stability of user receiving equipment become a problem. Most of the analysis presented in the reports is for a frequency of 8 GHz, but various side studies were carried out at 4 GHz to provide comparison information.

QUESTION 6

Q. Is the length of the antenna necessary to achieve the level of accuracy previously mentioned reasonable for a spinning satellite?

A. Yes.

Explanation (Volume III, Sections 1 and 2)

The ideal design of the antenna would be such that the narrow dimension of the fan beam is as small as possible (1^{o}-2^{o}). However, for the operational frequency previously suggested (8 GHz) and reasonable satellite spin rates (100 rpm), the upper bound on unsupported antenna length as dictated by structural and pattern considerations is approximately eight feet.

In the study, the effects of satellite rotation rate, antenna length, mounting angle and guying were considered. The parametric values and the results are indicated in Table 1. The parameters were varied one at a time with all other parameters having the nominal value. The nominal values are indicated by the outlined boxes. $\Delta\eta$ is the mean deflection of the radiated beam, $\Delta\phi$ is the deviation from the mean of the measured beam converted into an equivalent satellite rotation angle. The results are shown for two satellite altitudes, 5,000 n. mi. and synchronous (19,311 n. mi.). Altitude enters into these results in that the greater the altitude, the smaller the beam angle which will cover the earth; also, the deflected fan beam is more nearly planar in the neighborhood of the sub-satellite point.

The tabulated results indicate three significant facts:

a. The majority of the antenna deflection when translated into warping of the pattern ($\Delta\eta$) may be compensated for or calibrated out of the system. This would be accomplished by using an effective mounting angle for the antennas in the computations or using a predetermined offset in the physical mounting of the antennas.

b. The deviation of the warped pattern from the mean pattern is extremely small (1 microradian at synchronous altitude).

c. The effects of antenna warping are attenuated with increasing altitude due to the smaller segment of the beam being utilized at higher altitudes.

Table 1 Table of Antenna Deflections for Parametric System Errors

Parameter	Value	Mean Deflection of Beam $\Delta\eta$ (degrees)	Equivalent Rotation Angle Error of Satellite Due to Beam Deviation From the Mean $\Delta\phi$ (μ Radians)	
			Synchronous Altitude	5000 n. mi.
Antenna mounting angle, δ	30°	1.8	2.6	100
	$\boxed{45^\circ}$	1.9	0.51	10
	60°	1.6	0.044	0.4
Antenna length, L	45"	0.20	1.0	32
	64"	0.73	0.23	8.7
	$\boxed{84"}$	1.9	0.51	10
	103"	4.3	14.0	260
Spin rate, Ω	1 rps	0.49	0.085	4.2
	$\boxed{2 \text{ rps}}$	1.9	0.51	10
	3 rps	4.4	7.8	140
Guyed antenna		0.002	0.39	11

QUESTION 7

Q. Are satellite powers required for this accuracy level considered realistic in terms of satellite size and weight?

A. Yes.

Explanation. (Volume II and Volume IV)

The satellite RF powers required to achieve position accuracies of less than one nautical mile are shown in Figure 3. The individual curves are for receiver dish sizes ranging from 0.4 to 6.4 feet. A time increment of 30 seconds has been selected to reduce random timing errors at the receiver. It is important to note that this time increment required to eliminate random receiver errors could be eliminated in an operational system. This could be accomplished by using a phase-locked loop in the receiver which operates at spin frequency and smoothes the sum and difference times in an analog fashion. Once signal lock is achieved, the time-averaged signals would be continuously available and hence instantaneous position fixes could be achieved. If the user vehicle is undergoing rapid directional changes then an inertial system would be required to provide compensations for the satellite navigation system.

The satellite output RF power selected for an operational system, consisting of a wide variety of users and hence varied accuracy requirements (1 n. mi.- 2 n. mi.), would be in the range of 100 to 150 watts. This power requirement could be easily attained with a standard photovoltaic plus battery power supply on a spinning satellite and would require 130-190 watts of primary power. If the requirements are for accuracies of less than 0.2 n. mi. in position, then a lower altitude for the satellite would probably be required to retain these reasonable power levels. The asymptotic nature of the curves for higher powers and larger receivers arises from the fact that the deterministic errors such as spin-axis uncertainty, antenna mounting, etc., have been assumed as system constants and hence provide a limiting bias error in the position accuracy. If system calibration provides improved values for these constants, then a corresponding improvement in the limiting accuracy would be attained.

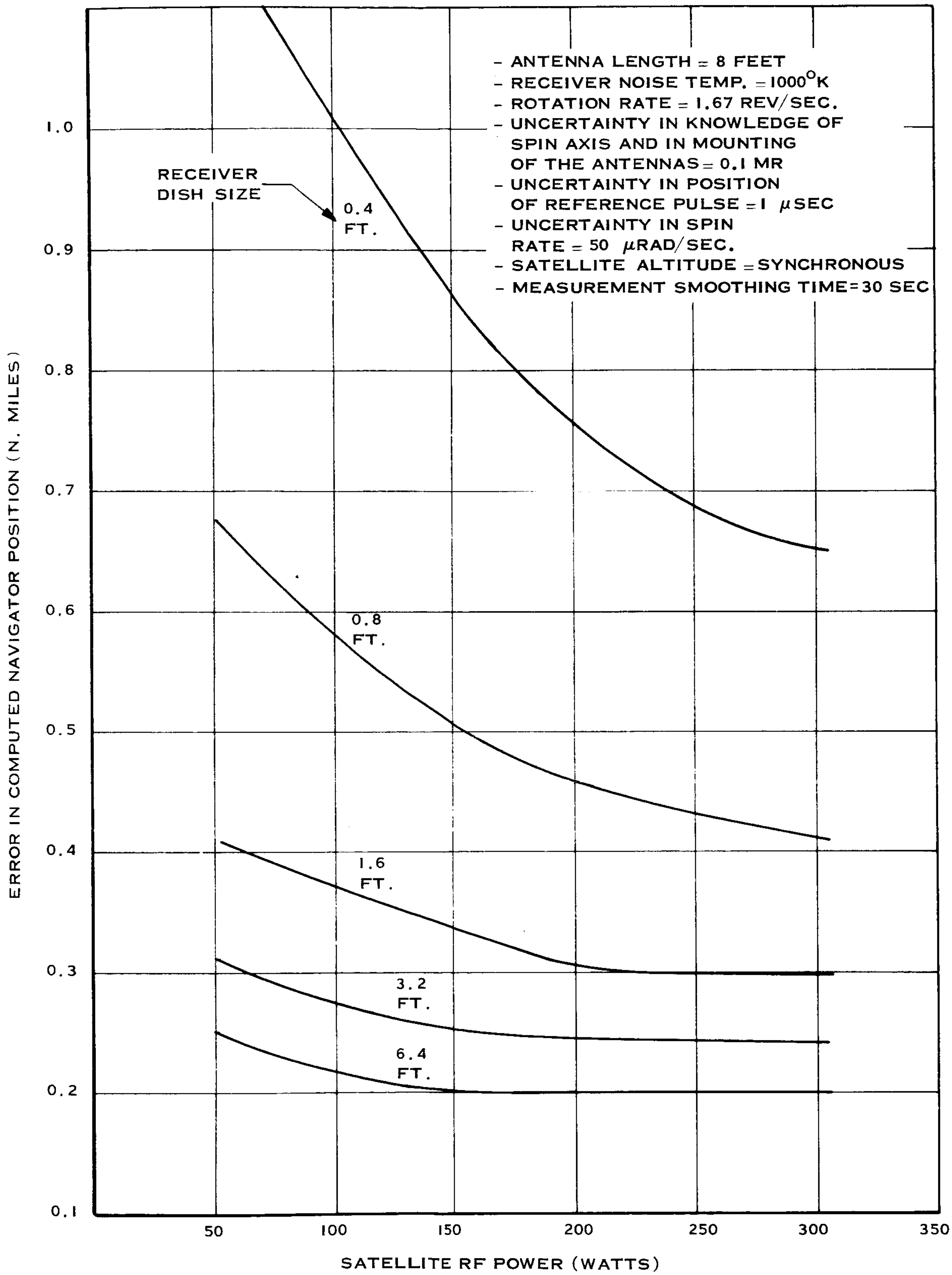


Figure 3 Position Error vs Satellite Power

QUESTION 9

Q. Is there a way to determine the satellite spin-axis orientation to the required accuracy?

A. Yes.

Explanation. (Volume V)

The determination of the spin-axis orientation in inertial space can be accomplished by one of two separate methods. First, the RF-sensed fan beams themselves may be used to solve for the spin-axis orientation. Errors due to antenna mounting. Fan beam generation and spin-axis misalignment will have to be established before the true spin-axis orientation is determined. A second method of acquiring spin-axis orientation is to use a star detector physically located on the geometric spin axis. The results of the study have shown that, using reasonably sized star detector optics (the total weight of the detector is 9 pounds) and a sophisticated digital data processing scheme, spin-axis orientation may be determined to an accuracy of 10 microradians and spin rate to an accuracy of 50 microradians/second. These accuracies are consistent with those required to attain the desired system accuracies.

In an operational system several calibration stations with large receiving antennas and low-noise receivers will most likely be used for spin-axis determination. If a star detector is used for reference pulse generation, it could also be used to determine any environmental effects on the spin axis such as that due to eclipsing.

QUESTION 10

Q. Is the required user receiver antenna relatively small?

A. Yes.

<u>Explanation</u>. (Volume IV)

As shown in the accuracy curves in Figure 3, a five-inch-diameter parabolic dish antenna can give an accuracy of one nautical mile after 30 seconds of data smoothing. This accuracy is based on a satellite RF peak power of 100 watts, a fan beam antenna length of 8 feet, and a receiver noise temperature of 1000°K. Larger antennas give better accuracies, all other parameters remaining unchanged. For example, 0.6 n. mi. accuracy is available if the user antenna is 10 inches in diameter. Similarly, a 20-inch antenna can provide 0.4 n. mi. accuracy. Aircraft might employ a fixed fan beam antenna consisting of a phased array of several radiating elements. An array that would provide the same gain as the 5-inch dish would be about one inch by 20 inches by about an inch deep, permitting it to be mounted on the outer surface of most aircraft.

QUESTION 11

Q. Does the receiver antenna require pointing?

A. Yes.

Explanation. (Volume IV)

The smaller antennas may need only initial pointing because of their relatively low directivity and because the satellite will most likely be geo-stationary. For example, the 5-inch 8-GHz dish would have a beam width of 20° which would permit use of an inexpensive set-and-forget type of antenna-pointing mechanism for non-maneuvering vehicles. In the case of the use of the phased-array fixed antenna with its fan horizontal, the beam may be pointed in several increments of elevation by switching of the phase control. Aircraft using this method would need little or no additional pointing while flying a straight-line course. Larger antennas for more accurate or quicker fixes require more frequent pointing. The 10 or 20 inch antennas may be pointed by hand, but in the case of moving vehicles automatic steering would usually be required. The larger dishes would be difficult to point by hand; for example, the 6.4-foot antenna has a 1.4° beam width which would make automatic acquisition and tracking mandatory.

QUESTION 12

Q. Is the receiver within state-of-the-art solid-state electronic capability?

A. Yes.

Explanation. (Volume IV)

All functional sub-units of the receiver may be realized using conventional transistor circuit design methods and component parts. A standard fixed-tuned superheterodyne receiver design will provide the necessary signal selection and amplification. Simple diode envelope detectors will demodulate the reference and measurement signals, and a PSK or FSK detector similar to that used in teletype receivers will demodulate the data signal. A phase-lock loop similar to that used in color television sync circuits is required in the reference demodulator output. Only the receiver input circuit and the local oscillator require advanced design procedures. Until recently, only expensive preamplifiers could provide the 1000 to 2000°K noise temperatures desired for this receiver. Recently developed Schottky-barrier mixer diodes indicate that 1000°K and 1500°K noise temperature receivers with no preamplifier are now feasible at 4 and 8 GHz, respectively. To achieve the frequency stability required of the local oscillator, a carefully temperature-compensated or oven-stabilized crystal oscillator is needed. Periodic calibration of the local oscillator may be desirable. However, transistor crystal oscillators with a long-term frequency drift of $1 \times 10^{-6} f_o$ are currently being produced. This stability is sufficient to ensure that the fan beam signal will be acquired with a conventional AFC circuit. Thus every circuit of the receiver may be designed using 1966 technology of transistor circuits.

QUESTION 13

Q. Does the cost of the receiver equipment appear to be compatible with a wide variety of users?

A. Yes.

Explanation. (Volume IV, Appendix A)

As stated in a letter from Applied Technology, Incorporated, the unit cost of the receiver in production quantities of 100 would be about $5000. This estimate is based on an 8-GHz receiver employing a tunnel-diode preamplifier, which itself currently costs $2000. Thus a receiver employing a low-noise mixer as described under Question 12 would cost in the neighborhood of $3000. The digital circuits required to translate the fan beam measurements to position coordinates are considered to be relatively simple and would not significantly increase the overall equipment cost. Considering the economy that would result from the production of the receiver in large quantities for an operational navigation system, it seems reasonable to expect that the receiver could be produced for $2500. This price would be compatible with the equipment budgets of a wide range of users. It has been stated that a navigation receiver in the price range of $2000-$5000 would be within the budgets of air carriers and shipping agencies.

QUESTION 14

Q. Does the system calibration appear to lend itself to long time intervals?

A. Yes.

Explanation. (Volume II)

When a precession-nutation damper is included in the satellite system, the time-varying angular velocity and fan beam normal vectors can be approximated at the times of the reference pulses by vectors fixed in space. Previous Philco WDL studies have shown that, for nearly equatorial orbits at synchronous altitude, the angular momentum vector should deviate less than 50 microradians per orbital period (the deviation is due to orbit regression and to the earth's magnetic and gravitational fields). The present study indicates that miscalibrations of 100 microradians are tolerable, except for the most demanding navigational requirements. Hence, recalibration at one or two day intervals should be sufficient.

For a satellite altitude of 5000 n. mi., a somewhat higher drift rate is present, but recalibration once per orbit period should still be adequate.

If the satellite does not itself generate the reference pulses (by means of a stellar or solar reference) but instead a calibration station issues them, then more frequent calibration may be required to keep the reference pulses synchronized with the satellite. This would be strictly a need of the calibration stations and would not affect the frequency with which updated reference vectors are issued for navigation.

QUESTION 15

Q. Could the fix computation required by a user be a relatively simple calculation?

A. Yes.

Explanation. (Volume II)

There are trade-offs among the various aspects of navigation by means of fan beams. One method of fix computation requires of the navigator only eight arithmetic operations (four multiplications and four additions), to obtain his latitude and longitude by a simple differential correction procedure. For this method, the calibration stations would have to provide a relatively large mass of data, covering a gridwork of earth-points over the operational area for the satellite. The entire mass of data would, of course, have to be updated periodically. For example, a grid size 30 n.mi. on a side results in a computational error of 0.3 n.mi.

Another fix computation method allows the navigator to estimate his latitude and longitude by means of polynomials involving the sum and difference of the detection times for the two fan beams. More arithmetic operations are required of the navigator (multiplications and additions -- no square roots or trigonometry) than for the differential method, while the amount of calibration data to cover the satellite's operational area would be considerably less.

In both of the above methods it is possible to obtain improvements in accuracy of the fix by enlarging the amount of data provided by the calibration stations.

The most accurate method of fix determination requires somewhat more effort from the navigator, including two square root calculations and three trigonometric evaluations. A small digital computer (perhaps paper-tape programmed) would be the best tool but a desk calculator could be used. For this method, a minimum of data is needed from the calibration stations.

QUESTION 16

Q. Does the reference channel required for this concept appear feasible to implement?

A. Yes.

Explanation

The reference channel requirements and possible implementation schemes were studied in detail. The guidelines followed in designing a practical reference channel were that errors due to the received reference should be small compared to fan beam channel errors and that the satellite transmitter RF power requirement should be similar to or less than that of the fan beam channel.

The timing accuracy required of the reference channel was derived as a function of satellite altitude, spin rate and desired position fix accuracy. It was found that for synchronous altitude, a 100 rpm spin rate, and a fan beam channel accuracy of 0.2 n.mi., the reference timing accuracy should be one microsecond or less to ensure that error due to the reference is much less than one mile. This precision may be achieved by a narrow reference pulse, a phased multiple tone reference, or a combination of the two.

The narrow pulse reference channel requirements were determined in terms of satellite peak power only. This was done by deriving the received pulse signal-to-noise density required as a function of timing accuracy. Required signal-to-noise ratio was determined by desired false-detection likelihood and bandwidth was determined by required timing precision. It was concluded that transmitter peak pulse powers required are greater than available space-application devices can provide in the 4 to 8 GHz band. A multiple pulse code was considered in lieu of the single pulse to reduce the peak power requirement. This approach, however, places the burden on the user equipment, for it would require digital code recognition circuits.

An alternative design investigated was a CW tone reference channel where the time reference is derived from the relative phase of the tones. This technique results in a low-power, continuously operating reference transmitter. Circuit implementation difficulties at low frequencies result in a reference channel design employing two tones plus a broad pulse. It was determined that satellite peak power for this reference signal is much less than that for the fan beam channel. A typical satellite-user electrical configuration was developed for this method and a block diagram is shown in Figure 4.

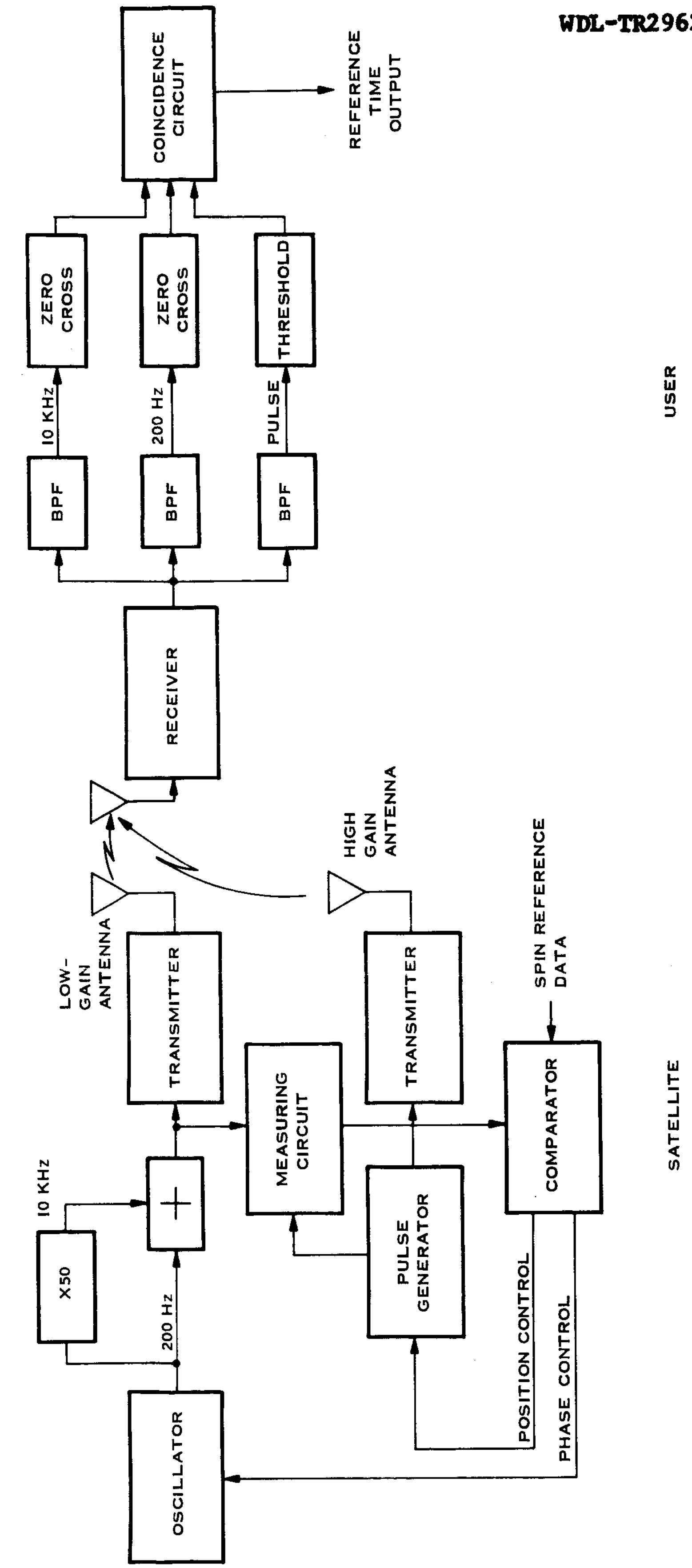


Figure 4 Simplified Block Diagram, CW Tone Reference Channel

QUESTION 17

Q. Should additional studies or tasks be carried out to refine any aspects of the system concept?

A. Yes.

Explanation

The study results indicate that several areas may require additional study before an operational system is evolved. The following tasks are felt to be the most significant:

a. Design, fabricate and place into orbit a navigation experiment as proposed in Volume V of this study. Make extensive studies of the results. This experiment will provide useful information required of many types of navigation concepts employing a spinning satellite.

b. Design a general-purpose receiver and breadboard it for experimental studies.

c. Design and build a breadboard model of the reference channel and conduct experimental studies.

d. Build a digital simulation for processing of simulated satellite data and perform system calibration studies. Use this program to conduct investigations on how calibration information should be optimally handled.

QUESTION 18

Q. It there a reasonable experiment which could be used to flight test this navigation concept before implementation of an operational system?

A. Yes.

Explanation

The problems associated with a fan beam navigational satellite were investigated in considerable detail during the period of this study. The detailed analytical results, as documented and presented in Volumes II-IV of this final report, indicate the definite feasibility of implementing an operational navigation system employing these techniques. However, before any operational system is implemented, it is necessary to verify analytical predictions and gain further information on the fan beam navigation technique by accomplishing an experimental test. The satisfactory flight-test verification of the concept and acquisition of flight performance data are the real goals of this experimental program. Once these have been accomplished and the currently predicted results are verified, an operational system could be evolved rapidly.

A navigation experiment was configured around a small spinning Synchronous Communications Satellite (SCS) developed by Philco WDL.

The new satellite configuration with additional equipment added is shown in Figure 5. Moment-of-inertia calculations and structural dynamic analysis were conducted to substantiate the vehicle's structural integrity and vehicle stability at the desired spin frequency of 100 rpm.

The new items of equipment as listed below have each been studied in considerable detail to determine development times and fabrication problems. There appear to be no critical problem areas in any of these subsystems which would require advancements in the state of the art or entail particularly difficult fabrication and testing problems.

Item	Weight
Command System	5 lb.
Battery System	16 lb.
Star Detector	9 lb.
Nutation Damper	1.5 lb.
Slotted Waveguides	5 lb.
Additional Telemetry Transmitter	5 lb.

The general program objectives and requirements are presented in Table 2.

The Navigation Satellite, as configured in this study, is small enough in size and weight so that it could conceivably be flown as a single primary experiment on a small launch vehicle or as a secondary experiment on a larger vehicle.

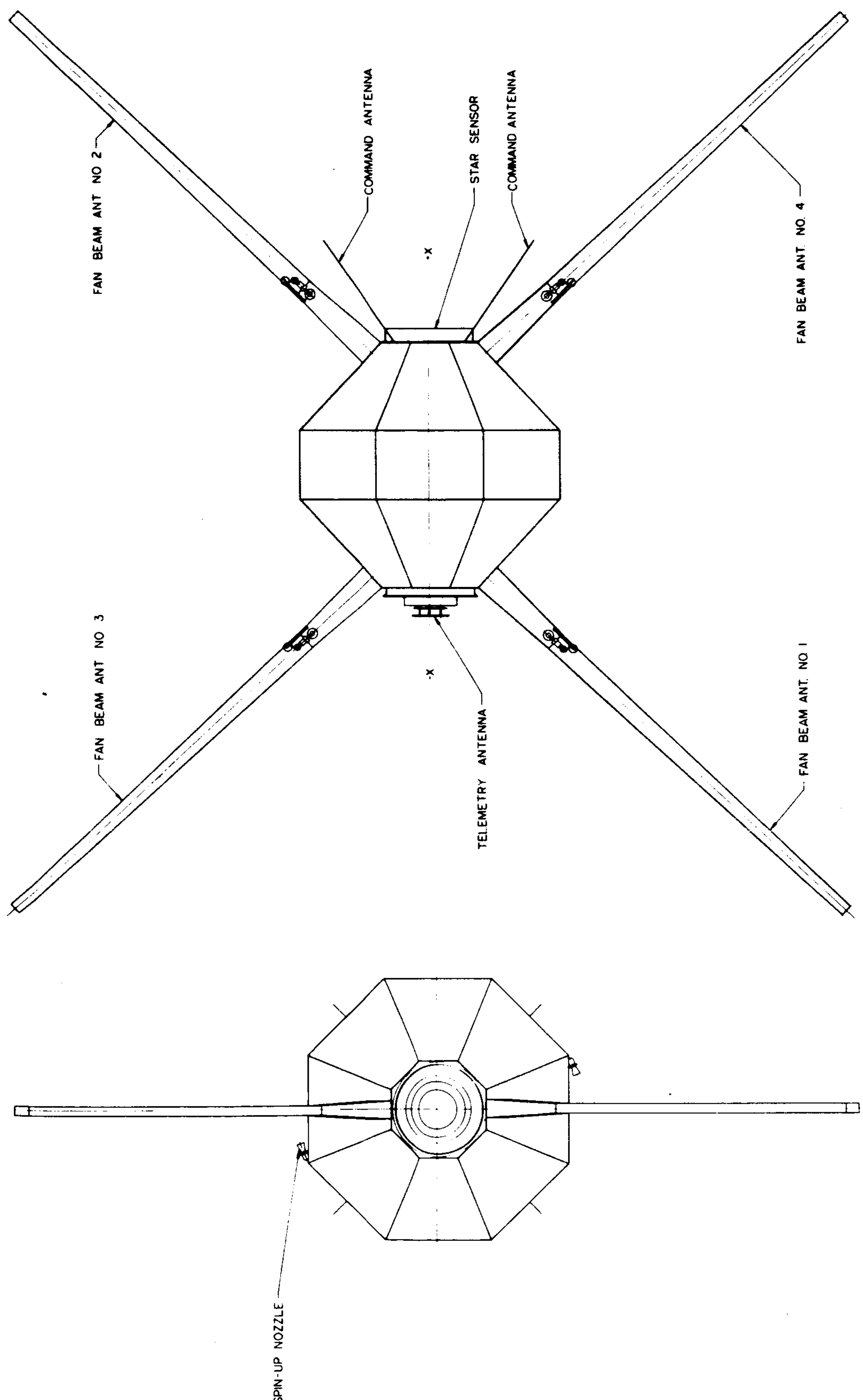


Figure 5 Fan Beam Navigation Experiment Satellite

Table 2 Program Requirements

	Requirement	Specification	Special Hardware Required	Comments
1.	Satellite Development	1 year	Standard (SCS) Structure	Maximum use is to be made of SCS Program experience technology, components, design and documentation in the Navigation Experiment integration. The basic SCS satellite will be fabricated and modified as required at Philco WDL. Qualification test will be accomplished at the subsystem and the satellite level.
2.	Launch Vehicle/Site	Open/AMR	Dispenser or spin table	Proposed configuration has self-contained spin-up capability.
3.	Mission Lifetime	1 year	None	For accomplishment of primary mission goals. Star Sensor Experiment may extend for a period of five years or to satellite deactivation.
4.	Hardware Development	State-of-the-art and flight qualified if available		
5.	Tracking Station Compatibility	NASA STADAN	8 GHz receiving equipment	Requires some receiver modification.
6.	Orbit Selection	Elliptical (100 n.mi. - synchronous altitude) $\pm 5.5^{o}$ inclination with respect to the ecliptic plane.	Reorientation of dispensing vehicle	Satellite would be injected into the transfer orbit for a synchronous mission. Time of launch must be fixed to attain proper orbit inclination.
7.	Attitude Stabilization	Spinning satellite with nutation damper. Spin axis normal to orbit plane.	Nutation damper	Self-contained Passive Mercury Damper.
8.	Attitude Determination	50-100 μ radians	Star detector	Similar to that proposed by WDL for NASA ATS-C
9.	Power Source	40 watts average, 75 watts peak	Photovoltaic/battery	
10.	Fan Beam Antennas	Slotted waveguides 4-feet long, 8 GHz	Honeycomb structure and waveguide	
11.	Telemetry Link	Two TLM transmitters at 400 MHz		Standard SCS hardware
12.	Command Link	125-150 MHz	Four whip antennas	Throughout orbit
13.	Orbit Determination	Less than 1 km in position	None	
14.	Data Collection	STADAN tracking network and smaller stations	Portable tracking stations (2' - 15')	Smaller stations could be Mascot type of mobile tracker.
15.	Data Processing	Digital data processing and system calibration	Software needs to be developed for data processing	Several data processing programs are already under development for the Star Sensor.

QUESTION 19

Q. Does this navigation concept allow for any satellite communication services?

A. Yes.

Explanation

As previously discussed in Question 7, the average DC primary power required for the navigation function, fan beams, and reference channel was estimated to be approximately 150 watts. If we assume a satellite having a total primary power of 300 watts, then one half of the total satellite power would be available for addition of communication services. This amount of primary power for communication services for a user antenna size of one foot diameter would allow for at least the minimum services shown below:

a. Periodic user position reporting to the air traffic control centers.

b. One air/sea search and rescue digital VOCODER channel.

c. Two digital VOCODER voice channels for communication to user aircraft.

QUESTION 20

Q. Would you recommend this navigation concept for use as an operational system?

A. Yes.

Explanation. (Volume I, Questions 1-19)

In light of the answers to the previous 19 questions it seems logical to consider this system as a strong candidate for an operational navigation system. However, a flight test experiment should be flown before any operational system is selected. A system comparison study should be performed including other types of navigation concepts to best exemplify the advantages and disadvantages of all concepts. It is felt that if this comparison were made, the concept presented herein would compare favorably with other navigation system concepts.